DEVELOPMENT OF A CAPP SYSTEM FOR ULTRASONIC MACHINING

by

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CERTIFICATE

This is to certify that the work contained in this thesis entitled ***Development of a CAPP System for Ultrasonic Machining*** by **Manas De** has been carried out under our supervision and that this work has not been submitted elsewhere for the award of a degree.

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ABSTRACT

The present dissertation deals with the development of a computer aided process planning system foe ultrasonic machining. Some of the existing models of material removal have been studied critically and some modifications have been proposed. The computer aided process planning system comprises of mainly three modules. The first module is for input to the system, the second module is for optimization of the process parameters using genetic algorithms and the third module gives the output of the optimal values of the process parameters for ultrasonic machining. The graphic user interface has been developed using Visual Basic language and the optimization code is written in C to suit the present problem. The package runs on IBM compatible PC-386 and onwards under windows environment.

Dedicated

to

my parents

(for sacrificing your dreams

so that mine could come true)

ACKNOWLEDGMENTS

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Chapter 1

INTRODUCTION

Recent advances in science and technology in the various fields of engineering have imposed severe demands on materials for making different types of components with special mechanical and metallurgical properties. This has given rise to the development of a wide variety of materials which are of high strength, high heat resistance, very hard and extremely brittle. Such materials are commonly termed as *difficult-to-machine* materials. Further, it is not only the machining of these materials that has posed newer and newer challenges to the manufacturing engineer, but also the narrow tolerances, complexity of the part geometry and the intricate shapes to be manufactured.

To cope up with the challenges, several *'unconventional machining'* methods have been developed in the past few decades. These methods are not affected by the hardness, toughness or brittleness of the work-piece material and are capable of producing intricate shapes with higher degree of accuracy. Some of the common unconventional machining processes are : Electric Discharge Machining (EDM), Abrasive Jet Machining (AJM), Chemical Machining (CHM), Laser Beam Machining (LBM), Ultrasonic Machining (USM) etc. Table 1.1 gives a comparative study of various unconventional machining methods.

Process	Energy source	Mechanism of material removal	Maximum MRR (cm^3/min)	Accuracy (micron)	Specific power consumption (kW/cm^3/min)	Typical machine power (kW)
ECM	Electric current	Ion displacement	16	50	8	200
EDM	Electric spark	Fusion & vaporization	5	12.5	2	10
USM	Mechanical motion of tool	Erosion	1	5	12	15
EBM	High speed electron	Fusion & vaporization	0.001	5	500	7.5
LBM	Powerful radiation	Thermal	0.001	12 5	3000	10

Table 1.1 Summary of various unconventional machining processes

1.1 Ultrasonic Machining

Ultrasonic machining (USM), conceived and developed by an American engineer *Lewis Balamuth* in 50's is an impact erosion process. A resonance transducer acts as the source of mechanical vibration, which transforms electrical energy into mechanical vibrations at a frequency ranging from 20 - 30 kHz. A mechanical amplifier, commonly termed as *Horn* amplifies the vibration amplitude at the output where the tool is attached. Abrasives in the form of slurry is fed into the work-tool gap by means of a nozzle. A special

mechanism maintains the static pressure of the tool against the work-piece. Material is removed by repetitive impact of abrasive particles against the work-piece surface in the form of microchips which are removed from the machining zone by the slurry. The shape of the resulting cavity thus formed is the inverse profile of the tool-form.

An overall improvement in the USM process performance -- higher machining rate and better surface finish are the main goals of USM manufacturers. Fig 1.1 shows a schematic layout of a typical ultrasonic machine. High frequency alternating voltage is applied through the excitation

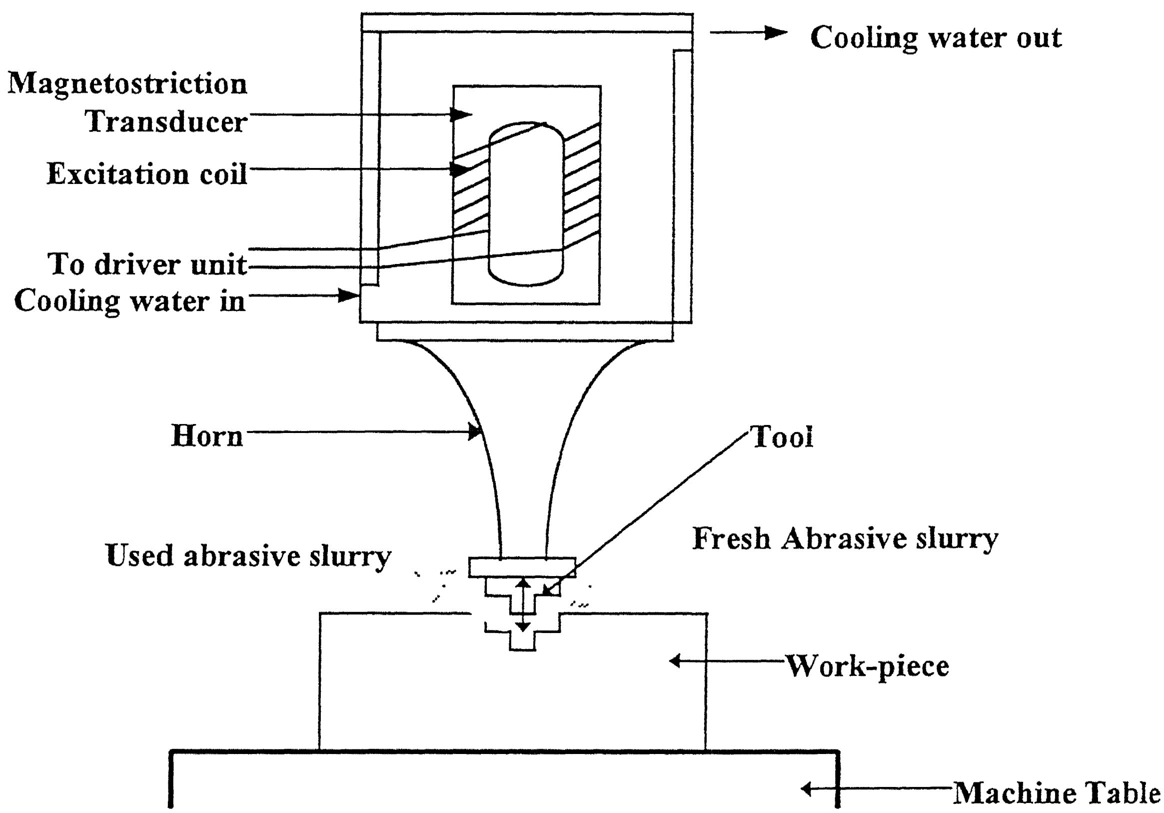


Figure 1.1 A schematic layout of Ultrasonic Machining Process

coil on the *magnetostrictive* transducer core. As a result of which the core gets lengthened and shortened. But the amplitude of vibration thus produced is not sufficient to be used in material process. The amplitude is amplified by using a mechanical amplifier, horn. The cross-section of the horn reduces in the direction away from the transducer. The tool is attached to the end of the transducer either by bolting or brazing. Care is taken to minimize the damping effects To carry away the heat generated in the transducer core, coolant (usually oil or water) is passed. The work-piece is mounted securely on the table, below the tool. In most cases the tool is moved up to provide the feed motion and to maintain a constant static feed-force..

1.2 Computer-Aided Process Planning

Process planning determines how a product, given its design, is to be manufactured and is therefore a key element in the manufacturing process. It bridges the crucial gap between designing and manufacturing of a product. It plays a major part in determining the cost of components and which in turn affects all factory activities, company's competitiveness, production planning, production efficiency and product quality.

There are numerous factors that affect process planning; such as shape, size, tolerance, surface finish, part material, quantity to be manufactured -- all contribute to and participate in the selection of machining operations, their sequencing and determination of the manufacturing parameters.

Since the process planning requires a great deal of judgment and even among the experienced engineers, there has been variations in judgments for the same product. To minimize the dependence on human skill so as to reduce discrepancies, computer assisted process planning is desirable. Incorporating logic, heuristics and experience required for process planning in computer programs have helped in automation of process planning.

There are two approaches used in CAPP; the ***variant*** process planning and the ***generative*** process planning.

The ***variant approach*** to some extent is similar to the traditional manual approach where a process plan for a new part is created by identifying, recalling and retrieving an existing process plan for a similar part from a computerized data bank and making necessary modifications for the new part. The variant approach is derived from the group technology (GT) methods where machined parts are classified and coded into files having similar manufacturing and/or design attributes. For each part family, a standard process plan is prepared and stored. This standard plan is restricted and edited for new parts

The ***generative approach*** utilizes the process information in order to create a process plan for a new part from the scratch. When the system receives the design model, it is able to generate required operations, sequences and the manufacturing parameters from the data available in its knowledge databases. The knowledge database contains the process know-how and equipment'

capabilities. A wide spread use of decision logic is made based on in-depth knowledge of manufacturing. Development of newer product designs, materials, methods and machines make generative approach an indispensable one.

1.3 USM and CAPP

Most of the work done in the field of computer-aided process planning relates to the conventional machining processes. Ultrasonic machining has started gaining popularity, but still it is not a very common machining process However the performance of USM largely depends on the operating parameters. CAPP for USM helps an individual, who may not be well versed with USM, to choose the operating parameters in a step by step interactive fashion so as to get the optimum machining performance

1.4 Steps of CAPP for USM

Process planning for ultrasonic machining involves :

1. Determining whether the given part geometry is machinable by USM process, or not.
2. Determining whether the required surface finish is attainable by the USM process., or not
3. Determining the type of abrasive to be used
4. Selecting the too material

5. Determining the USM parameters like
   a) Abrasive grit size
   b) Amplitude of vibration of the tool tip
   c) Frequency of vibration of the tool
   d) Concentration of abrasive slurry
   e) Required feed force
6. Predicting the expected material removal rate
7. Predicting the expected machining time

1.5 Motivation for the present work

Ultrasonic machining is perhaps the most widely used unconventional process. Various models of material removal has been proposed by different scientists. But most of them are either computationally very expensive; hence cannot be used in practice easily or overestimates the rate of material removal. Hence there has been a need for a model of material removal for the ultrasonic machining process which is computationally not very expensive, yet gives an fairly accurate material removal rate. Moreover since the awareness for ultrasonic machining in the industrial sector is very less, so in order to guide a novice to select the crucial machining parameters, so as to get maximum production efficiency, need for a CAPP system is felt. The present work is an attempt to fulfill these needs.

1.6 Organisation of the thesis

The organising of the thesis is as follows :

Chapter 2 discusses about the various models of material removal in USM, their shortfalls, and the proposed modifications to the model of material removal in USM.

Chapter 3 discusses in details the design of the proposed Computer Aided Process Planning system for Ultrasonic machining

Chapter 4 discusses in depth about the implementation of the proposed CAPP system. and illustrates the system with a few examples

Chapter 5 concludes with the scope of future work.

Chapter 2

MODELS OF MATERIAL REMOVAL IN USM

While the organized research about the ultrasonic machining process started in the 50's, it gained momentum in the 70's. The actual mechanism of material removal in ultrasonic machining is a complex phenomenon and is a combined effect of several factors. Viewing it from different angles, several research workers have proposed various models of material removal in ultrasonic machining. But neither of them can take into consideration all the aspects. Each model has some good aspects as well as some shortfalls. An attempt has been made in this chapter to study and present a critical review of the most commonly used models for determining the material removal rates (MRR) in ultrasonic machining process.

2.1 Some of the Existing Models

In this section, some of the of the popular models of material removal rate in ultrasonic machining have been discussed and analyzed.

2.1.1 Model Proposed by Miller

Perhaps one of the earliest models of determining the material removal rate in ultrasonic machining available is the one proposed by Miller (1957). The proposed model assumes the followings:

i) Abrasive particles have the shape of a perfect cube.

ii) Abrasive particles are of uniform size

iii) The material removal in brittle materials is due to chipping only whereas in the case of ductile materials it is due to plastic deformation and the consequent work-hardening.

iv) Vacuum exists under the tool tip area for a portion of time.

v) Plastic deformation is a linear function of time.

vi) Viscosity effects of the slurry is neglected.

Apart from the above assumptions, Miller has simplified the problem by taking the speed of deformation to be proportional to the frequency and that the abrasive slurry being accelerated in the machining zone due to the atmospheric pressure.

Finally, the model for material removal rate has been obtained in the following form :

$$MRR = \phi(PD)(TN)(WHR)(V_c)(R_c)(CR)$$

where,
MRR : material removal rate
PD : quantitative expression for plastic deformation
WHR : amount of work hardening
TN : total number of blows struck per seconds
V_c : volume of material chipped out on each blow
R_c : rate of coverage of tool tip area by the abrasives
CR : rate at which the chipping blows are struck.

After substituting for the various expressions in the above equation, the result in the final form has been obtained as:

$$MRR = M\frac{P_{st}dAY_aCf}{qG_1bR\rho_a v(C+1)}$$

where,

M	:	a constant
P_{st}	:	applied static load
A	:	half the height of machined ring
Y_a	:	atmospheric force
C	:	mass concentration of abrasives in the slurry
f	:	frequency of vibration
q	:	constant representing work hardening capacity
G_1	:	modulus of rigidity of work piece material
b	:	Burger's vector
R	:	radius of the machined ring
ρ_a	:	mass density of the abrasive
v	:	volume of slurry in the work gap.

It can be seen from the Miller's work that though the chipping blows and the total number of blows are differentiated, but no quantitative separation has been made. The work also lacks from the point of view of fundamental stress analysis. The machined ring radius calculated considering movement of the slurry as rigid body. However in practice the abrasive particles in the slurry are in random motion. Furthermore, the assumption that the speed of deformation is proportional to the frequency of vibration of the tool tip has no scientific basis. However, as a first attempt to theoretically study the mechanism of ultrasonic machining, it does depict many features of the process.

2.1.2 Model Proposed by Cook

The mathematical model of material removal in ultrasonic machining process proposed by Cook (1966) is based on the following assumptions:

i) Abrasive grains are spherical in shape and are of uniform radius R.

ii) The viscosity effect of fluid in negligible.

iii) Volume of material removed per impact is hemispherical in shape.

iv) A linear relationship exists between the fraction of active grits and the ratio of depth of indentation and the grit radius.

Finally Cook has obtained an expression of machining rate, V of the form :

$$V = 5.9 f\left(\frac{\sigma_s}{H}\right)(A.R)^{\frac{1}{2}}$$

where,

V	:	Machining rate (in/sec)
σ_s	:	static stress (psi)
f	:	frequency of vibration (Hz)
H	:	Hardness of work piece (psi)
A	:	Amplitude of vibration of the tool tip (in)
R	:	Radius of abrasive grains (in)

The model predicts linear relationship between the static stress and the material rate. However in practice, the MRR drops after a certain value of feed force has been reached. The model does not take into consideration of the viscosity effect of the slurry. The model predicts that the MRR is proportional to the square root of the radius of the abrasive grains. In

practice, it has been observed that MRR initially increases linearly with abrasive grain diameter and then drops down.

2.1.3 Model Proposed by Shaw

Shaw (1960) has proposed four different mechanisms of material removal in ultrasonic machining, viz., (a) impact of free abrasive particles deflected by the tool against the work piece, (b) hammering of abrasive particles into the work piece by the tool., (c) erosion due to cavitation and (d) chemical action associated with the slurry fluid. Of the above four mechanisms Shaw has analyzed the first two.

Material removal due to impact of the abrasive grains is based on the following assumptions :

i) The abrasive particles are spherical in shape and are of uniform diameter d.
ii) The volume of material chipped off the work piece surface is proportional to the cube of the impression diameter, caused by the impact.

The abrasive grains are pushed ahead of the tool and remain in contact with the tool when the tool accelerates in the downward direction. When the tool reaches the maximum velocity, the particles leave the tool surface and impinges on to the work piece with that velocity. If k is the probability of an impact of a given intensity to cause chipping of material from the work piece surface, then the material removal rate can be expressed as :

$$MRR_v = Ck\left(\frac{\pi^2 \rho_a A^2}{6\overline{\sigma}}\right)^{\frac{3}{4}} f^{\frac{5}{2}} d$$

where,

MRR_v	:	Material removal rate due particle impacting
C	:	Constant of proportionality
d	:	Diameter of abrasives
f	:	Frequency of vibration of tool
A	:	Amplitude of vibration of tool tip
$\overline{\sigma}$	:	Average stress due to the impact
ρ_a	:	Mass density of the abrasive particles

Assumptions in the analysis of material removal by hammering action is as follows:

i) The number of abrasives present in the working gap is assumed to be inversely proportional to the square of the abrasive diameter.

ii) The ratio of penetration of the abrasive grains into the tool face and the work piece surface is inversely proportional to the ratio of the hardness of the tool and the work piece.

iii) The volume of material chipped out from the work piece is proportional to the cube of the impression diameter formed on the work piece.

The maximum force that is transmitted by the tool on to the work piece occurs when the abrasives have penetrated into the work piece to the maximum depth. The rate of material removal due to the hammering action is given by :

$$MRR_h = c_1 \left(\frac{4AP_{st}}{\pi k(1+\lambda)\overline{\rho}} \right)^{\frac{3}{4}} fd^{\frac{1}{4}}$$

However, on the contrary that the material removal will decrease with the increase in the abrasive grain diameter, as predicted by the above equation, material removal rate increases with increase in the abrasive grain diameter. To avoid this contradiction, Shaw has assumed that the abrasive grains have an enveloping diameter, *d* and the grain surface is assumed to have a number of projections of diameter d_1. The force on the abrasive particles is proportional to d^2. The contact area is given by $\pi d_1 \delta_r$ which again is proportional to d^2. As contact area is proportional to the force, the penetration in the work piece is proportional to $\frac{d}{(d_1)^{\frac{1}{2}}}$. Thus $d_1 \propto d^2$. when this is incorporated in the original equation, material removal rate becomes proportional to the abrasive grain diameter.

The analysis done by Shaw is quite reasonable. It explores into the various possible mechanisms of material removal in ultrasonic machining. But still it has also some draw backs. Firstly the fragmentation profile is taken for granted to be spherical, not based on any solid foundation. The final expression is obtained only after manipulating with *d* and d_1. This model do not consider the viscous effect of the abrasive slurry, the difference in concentration inside and outside the work gap. The material removal rate obtained by utilizing this approach is on the higher side with that obtained by the experimental observations. However Shaw's analysis is perhaps the most

widely accepted one because of its simplicity and the ease of calculation of material removal rate.

2.1.4 *Model Proposed by Rozenberg*

Rozenberg (1973) perhaps the first researcher to incorporate the variability in size of the abrasive particles in the model of material removal in ultrasonic machining.. He has proposed a size distribution function which is found to be quite satisfactory. The size distribution function is given by :

$$\varphi(\varsigma) = \frac{1.095N}{\bar{\varsigma}}\left[1 - \frac{(\varsigma - \bar{\varsigma})^2}{\bar{\varsigma}^2}\right]^3$$

where,

$\phi(\varsigma)$	:	No of abrasive grains of diameter ς
N	:	Total number of abrasive grains
ς	:	diameter of any abrasive grain
$\bar{\varsigma}$	:	mean diameter of the abrasive grains

According to this model, since the abrasive grain size is non-uniform, as the tool moves towards the work piece, it comes in contact with a small number of relatively large sized abrasive grains. As the tool continues the downward motion, it touches more and more number of abrasive grains and some of the grains get crushed. The remaining grits penetrate into the work piece to varying depths depending on their size. When the tool is in a certain position, it looses all its kinetic energy and comes to rest. Rozenberg's formulation of the problem sounds to be quite realistic, but the solution is complicated and is computationally very expensive. Moreover, many empirical relations

have been introduced to obtain the final solution. Also there is a fundamental flaw as the chipped out volume is assumed to be pyramidal shape. The actual fracture profile has not been ascertained in the analysis.

2.1.5 Model Proposed by Kainth et al

Kainth's model (1979) of material in ultrasonic machining is perhaps a modified version of the model proposed by Shaw. This model assumes the followings:

i) The motion of the tool remains sinusoidal under the loaded condition.

ii) The abrasive grains are spherical in shape and follow Rozenberg's size distribution function.

The expression for the material removal rate is given as :

$$MRR = \frac{2.29Nf}{(1+\lambda)^{\frac{3}{2}}\bar{d}} \int_{x}^{d_m} \left[(d-x)d\right]\left[1-\left(\frac{d}{\bar{d}}-1\right)^{2}\right]^{3} dd$$

where ,

f	:	frequency of vibration
$\bar{d}$	:	mean diameter of the abrasive grains
N	:	number of abrasive grains in the working gap
λ	:	ratio of hardness of the work piece and the tool

The number of abrasive grains in the work gap, which is evaluated from the following equation:

$$N = \frac{C}{\left(\frac{1}{\rho_a}+\frac{C1}{\rho_f}\right)}\left(\frac{\pi D^2}{4}\right)\left(\frac{\bar{d}}{0.57\rho_a}\right)\left(\frac{\bar{x}}{\int_{d_0}^{d_m} d^3\left[1-\left(\frac{d}{\bar{d}}-1\right)^{2}\right]^{3}}\right) dd$$

where,

ρ_a	Density of the abrasive
ρ_f	Density of the carrier fluid
$\bar{x}$	Proximity distance between the too tip and the work piece surface.
D	Diameter of the tool
C	Concentration of abrasive in the slurry by weight

This model takes care of the size distribution of the abrasive grains as well as it follows Shaw's analysis. But the main drawback of this model is that it is computationally expensive, since it has to pass through a number of complicated equations in order to arrive at the material removal rate. The model predicts linear relationship between the material removal rate and the static force, which is not true always. The model does not take into consideration the differences in concentration inside and outside the machining zone. Moreover, the material removal rate predicted by this model is an order higher than that achieved in practice.

2.1.6 Model Proposed by Ghosh & Nair

The model proposed by Ghosh and Nair (1985) is based on the assumptions that

i) Abrasive grains are rigid spherical in shape and rest on a brittle half space waiting for impact.

ii) Each abrasive grain receives a single impact in the position considered.

iii) Abrasive grains are renewed after every impact.

The model is based on the fracture mechanics approach. The fracture profile is obtained by simulating the principle elastic wave propagation, the strain energy density distribution in a brittle half space, when a single rigid abrasive grit gives a single half wave displacement. The model requires rigorous mathematical treatment and cannot be used for practical purposes. However, this is perhaps the first model which predicts that the material removal rate will drops down with increase in the abrasive grain diameter when the grain diameter crosses a certain value.

2.1.7 Model Proposed by Wang & Rajkumar

Wang and Rajkumar (1996) have proposed a dynamic analysis of the ultrasonic machining process based on impact mechanics. They have framed the equations representing the dynamic contact force and stresses caused by the impinging abrasive grits on the work and solve them. The expression for the material removal obtained in this approach is given by :

$$MRR = cR\rho^{\frac{4}{5}} f^{\frac{8}{5}} A^{\frac{8}{5}}$$

where,

c	:	is a constant
R	:	is the mean abrasive grit radius
f	:	is the frequency of tool vibration
A	:	is the amplitude of vibration of tool tip
ρ	:	is the mass density of work piece

Though these model talks about the dynamic forces but it does not consider the fracture analysis, which would have been an ideal one. It introduces a gap constant of which nothing has been mentioned. This factor brings down the material removal rate by an order.

2.2 Selecting a Model for Proposed CAPP

The above discussion captures the advantages and disadvantages of various existing models. For a model to be used in Computer Aided Process Planning system should be simple and computationally cheap, yet gives the solution which does not deviate much with that obtained in practice. Considering the above facts the model proposed by Shaw seems to be ideal to be used in the development of the CAPP system for ultrasonic machining. Shaw's model is simple, computationally cheap and takes into account almost all the process parameters involved in ultrasonic machining process. Hence the model of material removal by the hammering action, proposed by Shaw has been chosen to be used in the CAPP for ultrasonic machining.

2.3 Modifications Proposed for the Selected Model

The above discussions show that each model has some good features and some drawbacks. To have a working model which gives material removal rate reasonably close to actual, a few modifications have been proposed. These modifications are discussed in this section.

2.3.1 Calculation of effective number of abrasive grains

One of the major drawback of Shaw's model is that it does not accommodate the variation of concentration inside and outside the machining zone. Hence the number of abrasive grains calculated is more than that actually present

and consequently gives higher material removal rate. To remove this drawback, the following modification is proposed:

Assumptions: Abrasive grains are spherical in shape and are identical having diameter d.

Notations used :

A	:	Amplitude of vibration of the tool tip
T	:	Time period of vibration
h_w	:	Depth of indentation in the work piece
h_t	:	Depth of indentation in the tool face
C	:	Concentration of slurry outside the machining zone
C_1	:	Concentration of slurry in the working zone
d	:	Mean abrasive grain diameter
ΔT	:	Time interval in which the tool is in contact with the abrasive grains.
λ	:	Hardness ratio of the work piece and tool material
S	:	Cross sectional area of the tool

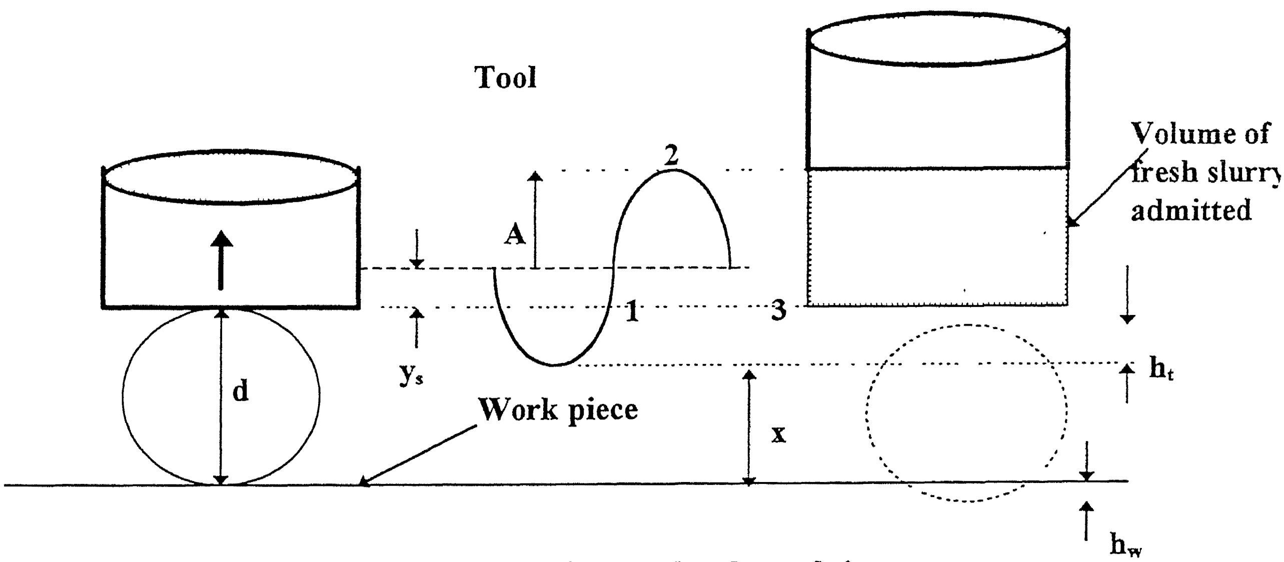


Figure 2.1 : Slurry flow under the tool tip

As can be seen from the figure, fresh slurry can be admitted in the working zone when the tool moves from position 1 to position 2. The volume slurry entered in the working gap is given as :

$$V_1 = (A + Y_s)S$$

Hence the number of abrasive grains entering in the working gap N_1 can be calculated as :

$$C = \frac{N_1 \frac{\pi d^3}{6}}{(A + y_s)}$$

$$\Rightarrow N_1 = \frac{6CS(A + y_s)}{\pi d^3}$$

When the tool reaches the top most position, the volume under the tool face V_2 is given by :

$$V_2 = (2A + x)S$$

The N_1 number of abrasives gets mixed up in the whole volume. Hence the new concentration of abrasive particles in the slurry can be obtained as :

$$C_1 = \frac{N_1 \frac{\pi d^3}{6}}{(2A + x)S}$$

While the tool moves down towards the work piece some amount of slurry is forced out of the machining zone, which takes away with a portion of the freshly admitted abrasive grains. The concentration of the slurry remaining in the working zone remains the same. So now the number of abrasive grains present in the machining zone is N_2.

$$C_1 = \frac{N_2 \frac{\pi d^3}{6}}{dS}$$

$$\Rightarrow N_2 = \frac{6CS(y_s + A)}{(2A + x)\pi d^2}$$

From the geometry we have :

$$h_w + h_t = A - y_s \qquad \text{and} \qquad h_w + h_t = d - x$$

$$\Rightarrow y_s = A - d + x$$

$$\Rightarrow x = d - h_w(1 + \lambda)$$

The depth of indentation of the abrasive into the work piece h_w can be obtained from Shaw's analysis as:

$$h_w = \left[\frac{8FA}{\pi d H_w (1 + \lambda) N_2}\right]^{\frac{1}{2}}$$

Hence the number of abrasive grains present in the machining zone is given by :

$$N_2 = \frac{6CS}{\pi d^2}\left[1 - \frac{d}{(2A + d - h_w(1 + \lambda))}\right]$$

Now, putting the value of h_w in the above equation we can solve for N_2. by iteration. The number of abrasive grains calculated by this method is much less than that compared to the number of abrasive grains calculated by conventional method. Using the reported experimental data [Kainth, 1979], material removal rates have been calculated using Shaw's model with and without incorporating the proposed modification for calculating the number of abrasive grains in the machining zone. The plot shows that the proposed one closely resembles the experimental observations.

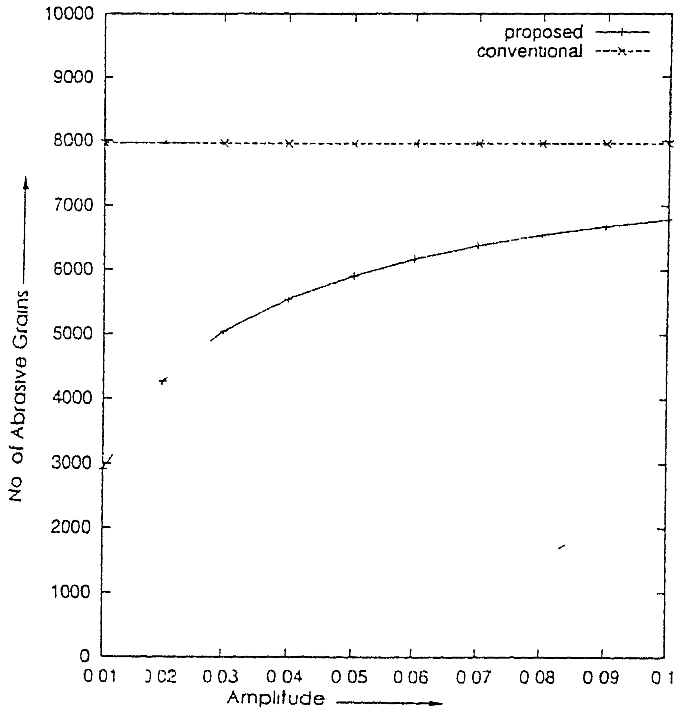


Figure 2.2 : Plot showing the comparison of number of abrasive grits in the machining zone

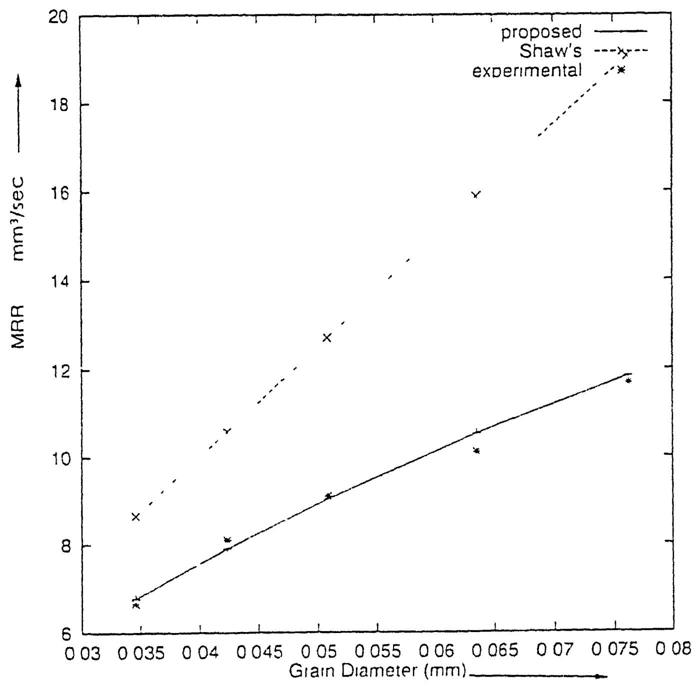


Figure 2.3 : Comparison of material removal rates

2.3.2 Calculation of Machining Time

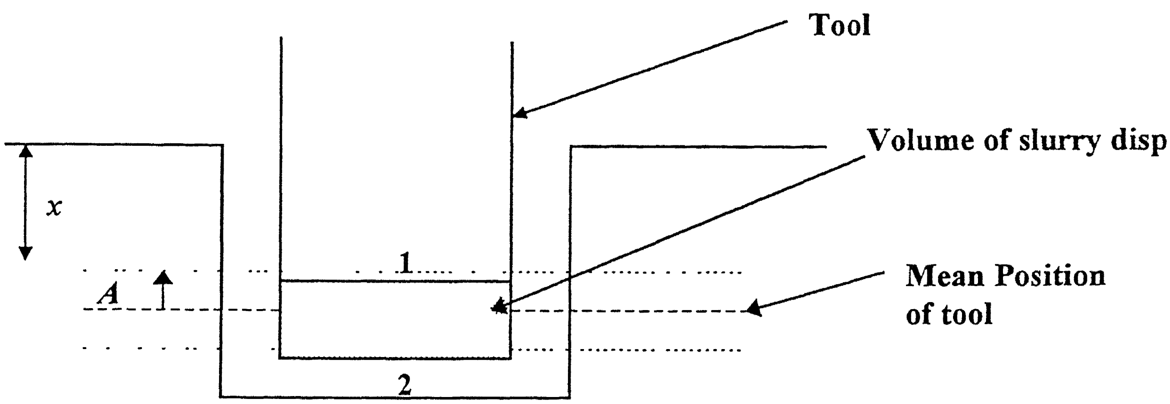


Figure 2.4 : Abrasive renewal in ultrasonic machining

Notations used :

S	:	Cross sectional area of the tool
P	:	Perimeter of the tool
d_1	:	Mean diameter of abrasive grain
C	:	Volume concentration of slurry
MRR_x	:	Material removal rate at machining depth x
v	:	Volume of material removed per impact per grit
f	:	Frequency of vibration of the tool
A	:	Amplitude of vibration of tool tip

When the tool moves down from position 1 to position 2, the used up slurry of volume V_1 is given by:

$$V_1 = 2AS,$$

is forced to rise through the annular clearence zone. The clearence is taken to be d Hence the cross sectional area of the clearence zone is Pd. When the tool moves in the upward direction, it sucks slurry into the machining zone. For machining depth x, volume of slurry that can be accomodated in the clearence zone V_2 is expressed as:

$$V_2 = Dd_1x$$

Therefore, the volume of fresh sluury admitted in the machining zone V can be obtained from

$$V = V_1 - V_2 = 2AS - Pd_1x$$

Number of new abrasive grains entering in the machining zone N, is given by

$$N = \frac{6C(2AS - Pd_1x)}{\pi d_1^3}$$

and the corresponding material removal rate is obtained as $MRR_x = vNf$

Let, Δt is the time interval required to increase the machining depth from x to $x + \Delta x$. Therefore, the value of Δt can be expressed as :

$$\Delta t = \frac{S\Delta x}{MRR_x} = \frac{\pi d_1^3 \Delta x}{6C(2AS - Pd_1x)vf}$$

Therefore, the penetration rate at depth x is given by

$$\frac{\Delta x}{\Delta t} = \frac{6C(2AS - Pd_1x)vf}{S\pi d_1^3}$$

As, $\Delta t \to 0$, we can modify the above equation as:

$$\frac{dx}{dt} = \frac{6C(2AS - Pd_1x)vf}{S\pi d_1^3}$$

So, the total time for machining a hole of depth h can be obtained as

$$t = \int_0^t \Delta t = \frac{S\pi d_1^3}{6cvf} \int_0^{h-2A-d} \frac{dx}{(2AS - Pd_1x)}$$

$$\Rightarrow t = \frac{\pi d_1^2 S}{6CvfP} \ln\left[\frac{1}{1 - \frac{Pd_1(h - 2A - d_1)}{2AS}}\right]$$

From the above equation, it can be said that the maximum depth upto which machining can be done is given by

$$h_{max} = \frac{2AS}{Pd_1} + 2A + d_1$$

Unfortunately, no reported experimental data depecting the variation of machining rate with the depth of machining could be found. The plot of machining time vs depth of machining however quantatively verifies the fact that machining rate decreases with depth of machining.

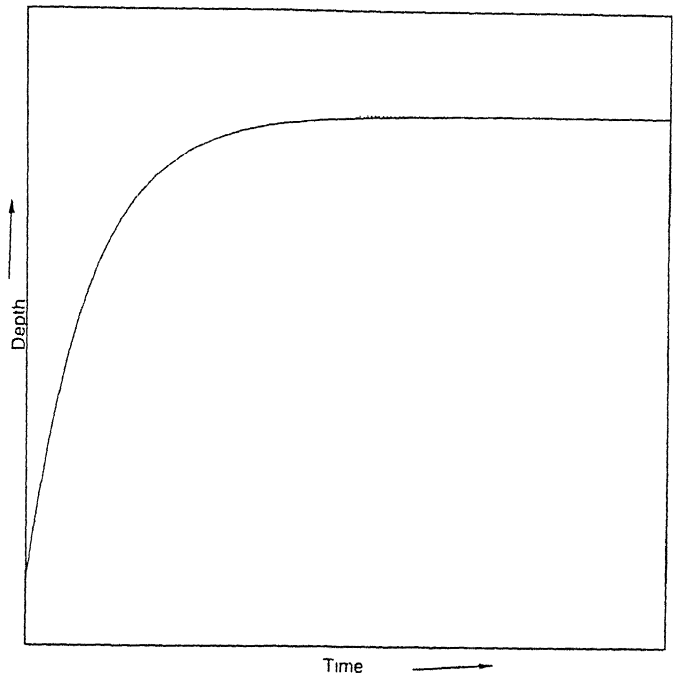


Figure 2.5 : Variation of machining time with depth

Chapter 3

DESIGN OF THE PROPOSED CAPP

The salient features of a CAPP for USM are given in this section. In the present work, it is proposed to design and implement a CAPP for USM. It is proposed to have the following modules in the system:

- Input of the part geometry
- Checking if the part can be manufactured by ultrasonic machining, or not
- Input of other parameters, such as work-piece material, abrasive type etc.
- Determination of optimum operating parameters.

3.1 Input of the part geometry

One of the foremost requirement for development of a CAPP is to provide the geometrical data about the part to the system in an unambiguous form. For this purpose, data about two major views in terms of longitudinal and transverse cross-sections are to be specified. The longitudinal cross-section can be viewed as a closed polygon where the vertex points are to be specified. The transverse cross-section can either be circular, regular polygonal shape or may be anything that can be approximated to closed polygon.

For longitudinal cross-section, the user is required to specify the coordinates of the vertices of the polygon. For transverse section, the user is required to

specify the shape of the cross-section and a few other parameters to completely define the part.

3.2 Checking for the machinability of the part

A part can be machined by ultrasonic machining process if the entire portion of the surface to be machined is approachable by the tool from the direction of matching. Or in other word, a part can be manufactured by USM if the entire surface to be machined is *visible* from the direction of machining `***Visibility test'*** provides a convenient way to carry out this work.

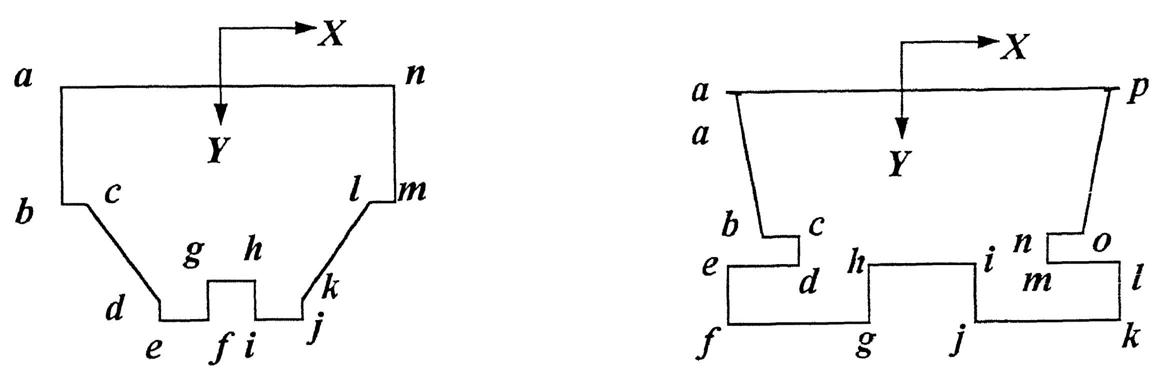


Figure 3.1 : Illustrative examples for vissibility test

The part geometry specified in fig. a is such that all the surfaces to be machined (viz. *ab, bc, cd,* ....) are visible from the top (i.e., along the positive y direction). But the part geometry specified in fig. b cannot be manufactured by USM, since the surfaces *de, ef, fg, jk, lk* and *ml* are not completely visible along positive y direction. Based on the above observations, the following algorithm is proposed for checking of machinability in USM.

Visibility Algorithm for USM :

1. Get coordinates of all the vertex points (i.e., x_i s and y_i s) in anticlockwise sequence, starting from the top-left vertex (e.g., point `*a*' in fig. a).
2. Identify the j^{th} vertex point having the maximum y coordinate value. In case of a tie, take the first one.
3.

a) ***For*** $I = 2$ ***to*** j

If x coordinate of the I^{th} vertex $>$ x coordinate of $(I - 1)^{Th.}$ vertex

Then $[I, (I - 1)]$ face is not completely visible from the top.

i.e., USM is not feasible, ***Exit***

Else

Continue

b} ***For*** $I = (j + 1)$ ***to Number of vertices***

If x coordinate of the I^{th} vertex $<$ x coordinate of $(I - 1)^{th}$ vertex

Then $[I, (I - 1)]$ face is not completely visible from the top

i.e., USM is not feasible, ***Exit***

Else

The part can be machined by USM

If a part geometry successfully crosses the visibility test, then the ***slenderness ratio*** is calculated. If the obtained ratio is within a specified range, then the part can be manufactured by USM.

3.3 Inputs for other parameters :

This module provides input for the following :

a) Work-piece material

b) Abrasive type

c) Tool material

d) Required surface finish

The approach for providing the inputs is by selection of appropriated value from a list of several values already stored in the database. Work-piece material is to be selected from the list provided. If the desired material does not figure in the list, the database can be appended suitably to accommodate the new material. Once the work-piece material has been chosen, an appropriated tool-material and abrasive types are shown to the user as default values. However, the user may change them by selecting other options from the lists

The selection of abrasive grains to some extent depends on the work piece material. However there is no concrete rules. Based on the reported experimental observations, it has been found that Aluminium oxide is best suited for glass, ceramics and hardened steels; whereas silicon carbide gives better results with carbides, hard alloys (Ghosh). Because of high cost, diamond is rarely used as abrasive in ultrasonic machining process.

One unique feature of ultrasonic machining is that the tool material is softer

than the work piece material. Stainless steel is widely used as tool material because of its easy availability,good machinability and is economically viable. Cast steel is also used as tool material.

Required surface finish grade is chosen from the list comprising of rough, fine, smooth and ground. The list also provide information regarding the expected tolerance and surface roughness.

Surface finish grade	**Maximum surface roughness (microns)**	**Suitable range of total tolerance**
Rough	65	0.001 - 0.01
Fine	32	0.0005 - 0.001
Smooth	15	0.0002 - 0.0005
Ground	5	0.0001 - 0.0002

Table 3.1 : Surface finish grades

3.4 Determination of Optimal Operating Parameters:

Performance of USM is very much dependent on the selection of various operating parameters, such as

- Amplitude of vibration of the tool tip
- Frequency of vibration of the tool tip
- Feed force
- Abrasive grit size
- Concentration of the abrasive slurry

The main objective is to maximize the production rate; i.e., to maximize the material removal rate, subjected to the various constraints. The constraints includes the amplitude of vibration, frequency of vibration, feed-force, slurry concentration -- each should lie within a specified range and the expected roughness height which has to less than the specified value.

3.4.1 Formulation of the Optimization Problem :

Objective function : Maximization of the material removal rate, *MRR*. [Shaw(1960)].

$$MRR = \left[\frac{8FAC}{H_w (1+\lambda)} \right]^{\frac{3}{4}} d_{avg} f$$

where,

F	:	Feed force (N)
A	:	Amplitude of tool tip vibration (mm)
f	:	Frequency of tool vibration (Hz)
C	:	Abrasive slurry concentration (volume %)
H_w	:	Hardness of work piece (N/mm^2)
λ	:	Hardness ratio of work piece and tool material
d_{avg}	:	Average abrasive grain diameter (mm)

Constraints:

(a) Amplitude of tool tip vibration A, should be in the following range,

$$0.005mm \le A \le 0.10mm$$

(b) The range of frequency of tool vibration is given by

$$20000Hz \leq f \leq 30000Hz$$

(c) Feed force range is specified as

$$1N \leq F \leq 10N$$

(d) Volume concentration of abrasive slurry C, should be in the range

$$5\% \leq C \leq 30\%$$

The surface roughness height $h_w = \left[\frac{8FAd_{avg}}{6CSH_w(1+\lambda)}\right]^{\frac{1}{2}}$, where S is the tool cross sectional area should be within the range as specified by the user in the form of surface roughness grade.

3.4.2 Solution Methodology -- Genetic Algorithms :

The above formulated optimization problem can be solved by any nonlinear optimization method. In this chosen work it has been solved by using Genetic Algorithms (GAs). Genetic Algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection. In Simple Genetic Algorithms (SGA), the variables are coded as binary strings. The length of a string depends on the desired accuracy in that variable. A fitness function ***F(x)***, derived from the objective function, is maximized in Genetic Algorithms. In the present case ***F(x)*** is taken as the material removal rate (***MRR***).

The operation of Simple Genetic Algorithms (SGA) begins with a ***population*** of binary coded strings of decision variables. The population is then operated by three operators; namely ***reproduction, crossover*** and ***mutation***.

In ***reproduction***, good strings in a population are probabilistically assigned a larger number of copies and a mating pool is formed. In ***crossover***, new strings are created by exchanging information among strings of the mating pool. The ***mutation*** operator changes 1 to 0 and vice versa with a small mutation probability, thus creating a neighbouring point of a current point. This facilitates local search around a current solution. The new population thus formed is evaluated and tested for termination. If the termination criterion is not met, the population is itteratively operated by the above three operators until the termination clause is satisfied. Thus in Genetic Algorithms,

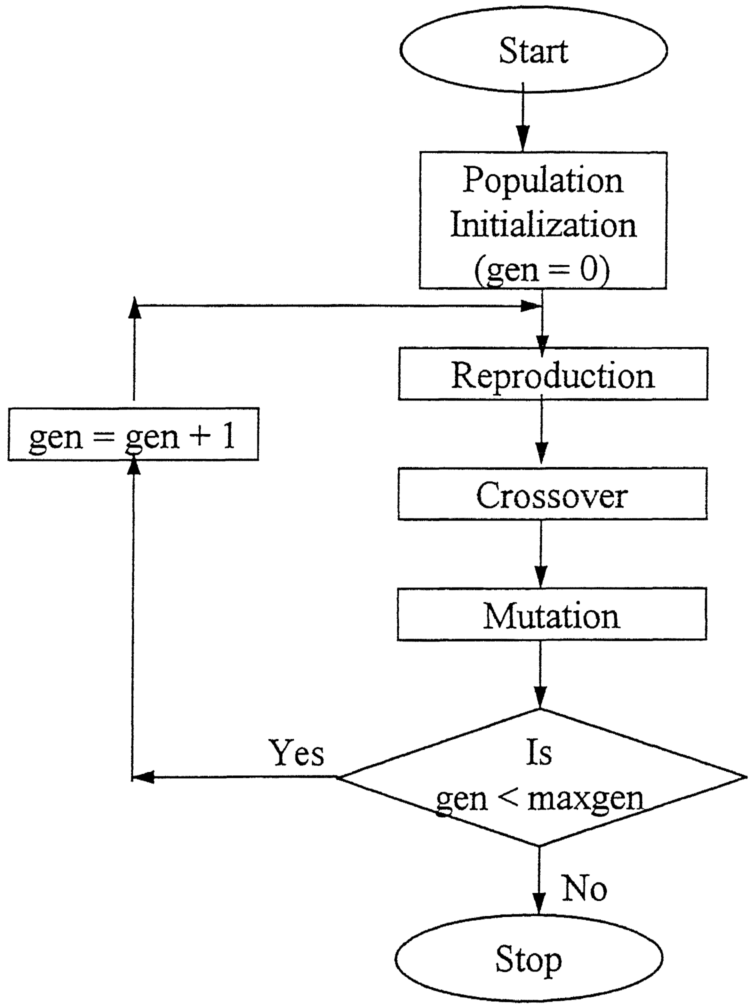


Figure 3.2 : Flow chart of simple genetic algorithm

previously found good information is emphasized using reproduction operator and propagates adoptively through crossover and mutation operators. The major steps of a general SGA are shown in figure 3.2.

After a series of hit and trial the following SGA parameters are chosen :

Number of generations	=	30
Population size	=	100
Cross over probability	=	0.9
Mutation probability	=	0.01
Number of variables	=	6
Convergence and closeness epsilon	=	0.001

The program for SGA has been taken from Deb (1990) and is modified accordingly to suit the present problem.

IMPLEMENTATION AND RESULTS

The proposed CAPP system for USM as a software package has been developed using Visual Basic and C languages. Visual Basic has been used to create the Graphic User Interface (GUI) and also to perform computational works to some extent. The procedures for optimization have been implemented using Bordland C++ compiler.

The user specifies the inputs in Visual Basic environment. The inputs are passed on to the optimization routine. The optimal values of the parameters are returned and displayed on the Visual Basic environment. The package runs on any IBM compatible PC-386 and onwards in Windows environment. It is not essential that the computer on which it runs should be loaded with Bordland C++ and Visual Basic compilers unless modifications to the package is needed.

4.1 Inputs to the System

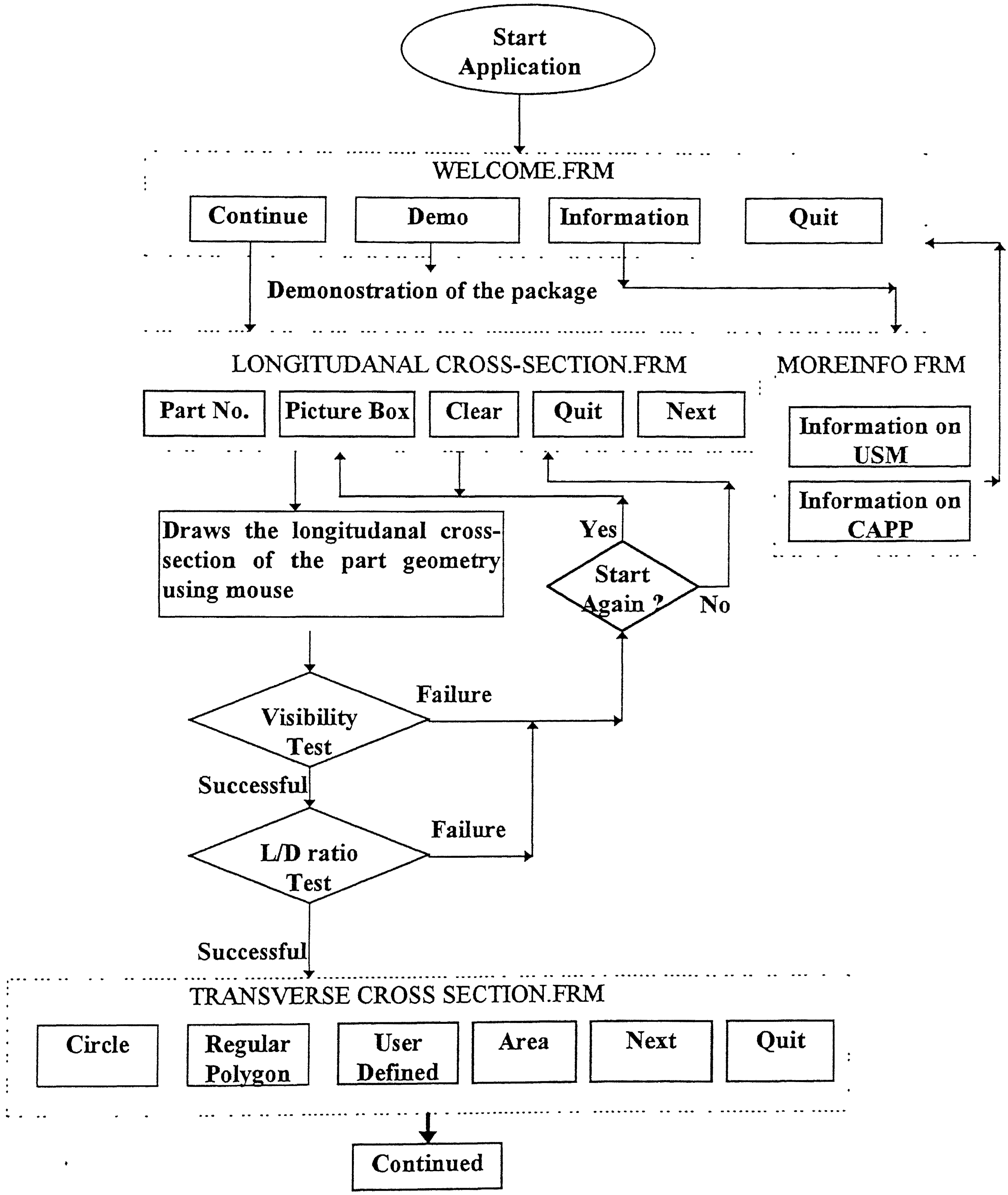
1. Longitudinal cross-section of the work-piece geometry
2. Transverse cross-section of the work-piece geometry
3. Work-piece material
4. Type of surface finish required

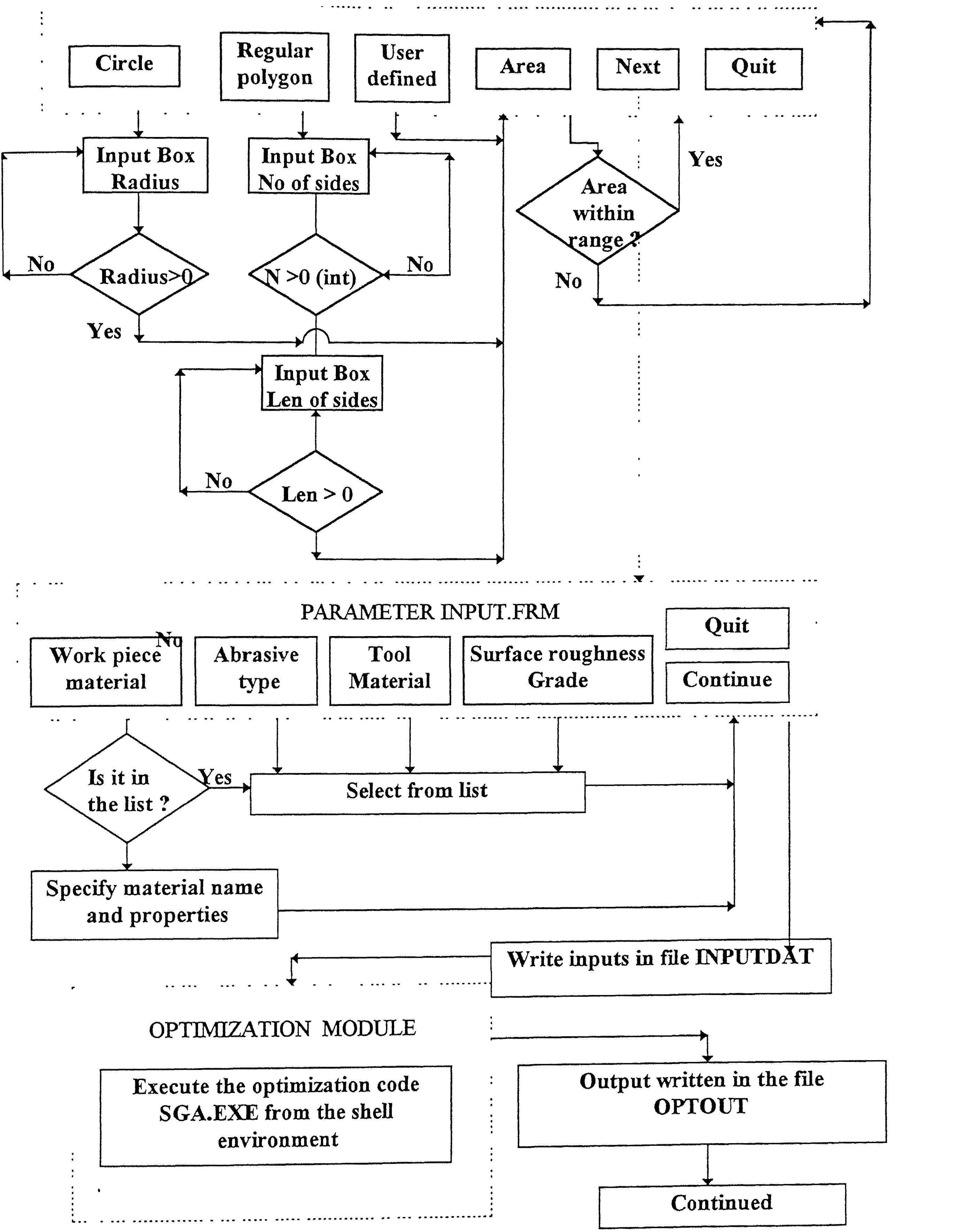
The user is required to give the inputs in the sequence they are asked. Efforts have been made to make the package user-friendly. Most of the inputs (viz., specifying part geometry, selecting work-piece material etc.) can be done using mouse clicks. Hot keys have also been provided for those who are more comfortable with the key-board. A demonstration program has been incorporated to make the user acquainted with the system. On line helps have been provided at the critical places. Checks and error messages have been incorporated at most of the places.

4.2 Outputs of the System

1. Types of abrasive to be used
2. Abrasive grit size to be used
3. Concentration of the slurry to be used
4. Tool material to be used
5. Required amplitude of vibration of the tool tip
6. Required frequency of vibration of the tool
7. Feed force to be applied
8. Expected material removal rate
9. Expected machining time
10. Expected surface roughness

4.3 Flow Chart of the Software package





Circle
Regular polygon
User defined
Area
Next
Quit
Input Box Radius
Input Box No of sides
Area within range ?
Yes
No
Radius>0
N >0 (int)
No
No
Yes
Input Box Len of sides
No
Len > 0
PARAMETER INPUT.FRM
Quit
Continue
Work piece material
No
Abrasive type
Tool Material
Surface roughness Grade
Is it in the list ?
Yes
Select from list
Specify material name and properties
Write inputs in file INPUTDAT
OPTIMIZATION MODULE
Execute the optimization code SGA.EXE from the shell environment
Output written in the file OPTOUT
Continued

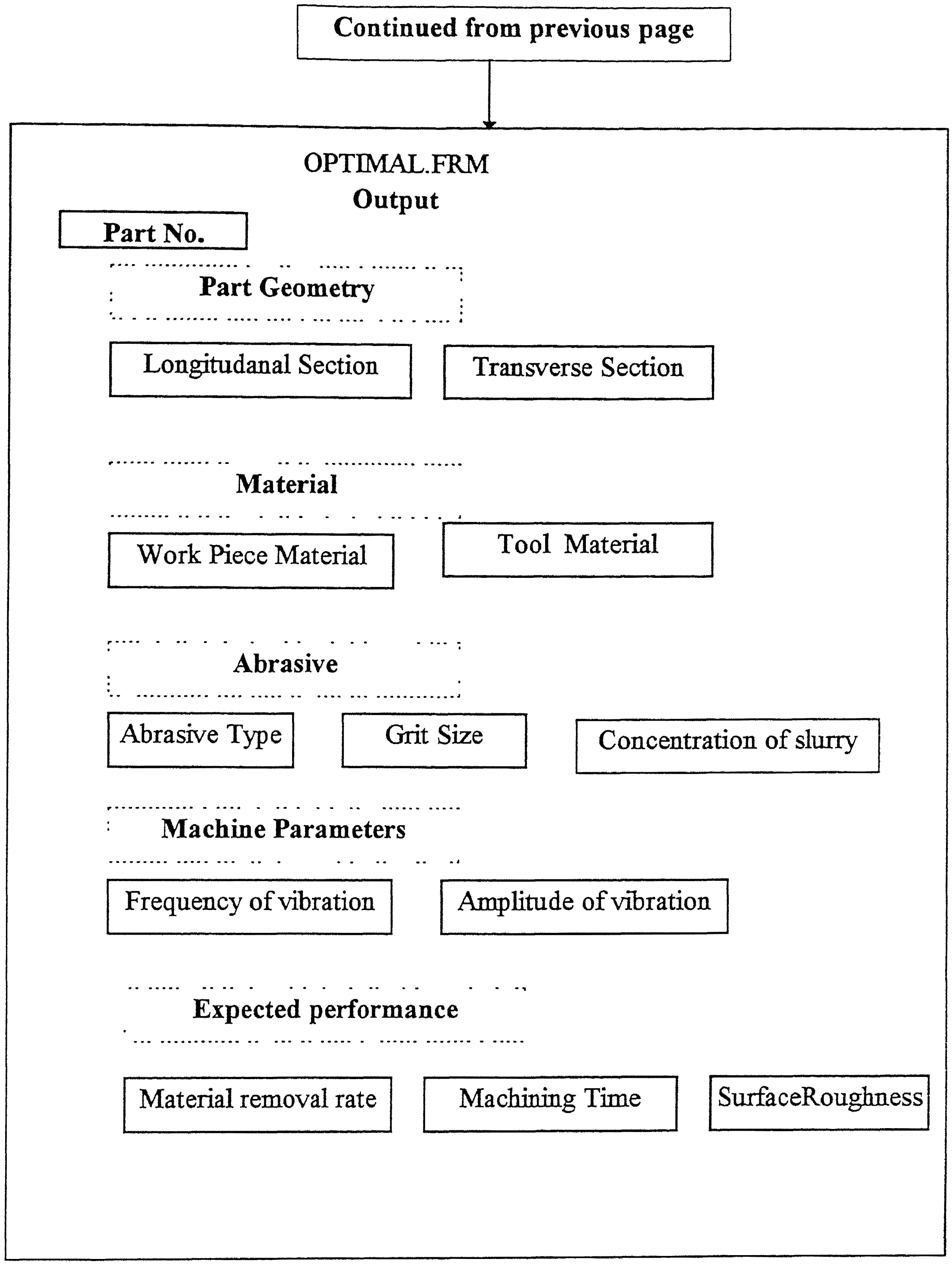


Figure 4. 1 : Flow chart of the software

4.4 System Files

In Visual Basic a ***project*** consists of a group of files. Each ***form*** is saved separately with .FRM extension and each ***code*** module is saved in files with

.MAK extension. The project file containing the information of various codes and forms used in the project is saved as a .MAK file. The executable version with .EXE extension can be run under windows environment.

The optimization code originally written in C has been modified accordingly so as to suit the present problem and compile with Bordland C++ compiler. Apart from these there are a few files written in the text format used as database, e.g., material properties, tolerances and surface roughness values, machine database.

List of Files

Visual Basic Files	C Files	Data Files
USM.MAK	SGA.C	SurFin.dat
USM.EXE	SGA.EXE	Mat.dat
USM.BAS		inputdat
WELCOME.FRM		optout
INFO.FRM		Machindata
MOREINFO.FRM		
USMINFO.FRM		
CAPPINFO.FRM		
LONG_CS.FRM		
LCS_HELP.FRM		
TRANS_CS.FRM		
PARA_IN.FRM		
OPTIMUM.FRM		

Table 4.1 : List of system files

Some of the controls used in the application has been listed below.

Name Prefix	Control	Description
pic	Picture Box	Provides a rectangular area in which graphics can be displayed.
lbl	Label	Displays text that the user cannot modify at run time.
cmd	Command	Responds to a user click to activate an events.
txt	Text Box	Displays text that the user can modify at run time.
cbo	ComboBox	Displays list of data. The user can select a value either by typing in the edit area or by selecting from the list.

Table 4.2 : Visual Basic Controls

The project file USM.MAK is the record of the forms and USM.BAS contains the global declarations. Each form contains several controls e.g., label, text box, picture box, command button etc. Each control contains one or more procedures like mouse-click, mouse-double click, key up, key down, got focus, lost focus etc. Each procedure performs a definite action when invoked. The list given below shows the various form names, its controls, procedures and the action performed.

Form Name	Control Name	Procedures	Action Performed
WELCOME.FRM (First slide shown)	cmdContinue	mouse_click	Hides Welcome.frm Shows Long_CS.frm
	cmdInfo	mouse_click	Hides Welcome.frm, shows the information page Info.frm

contd...

Form Name	Control Name	Procedures	Action Performed
	cmdContinue	mouse_click	Hides Long_CS.frm and shows Trans_CS.frm, but if the user presses this button before specifying the longitudanal cross section, MESSAGE BOX saying without it the package cannot proceed.
TRANS_CS.FRM	cmdCircle	mouse_click	INPUT BOX for entry of radius pops up. The required form is displayed on the picture box. If anything else other than a positive number is specified, Error message is shown in the MESSAGE BOX.
	cmdRegular Polygon	mouse_click	INPUT BOXES for the entry of the number of sides and the length of each side appears on the screen. If any illegal entry is made, Error message is shown in the MESSAGE BOX. Otherwise the specified geometry is drawn on the picturebox
	cmdUser	mouse_click	The picture box is enabled and set focus
	picture	left mouse button click	Specifies the vertex points of the user defined shape and joins them with straight lines.
	picture	middle mouse button click	Joins the last and the first specified vertex points and computes the area of the geometry. If it is more than a specified value, MESSAGE BOX informs it to the user.

contd...

Form Name	Control Name	Procedures	Action Performed
	picture	right mouse button click	Clears the Picture Box area and asks for fresh drawing
	cmdNext	mouse_click	If the inputs given in the form are acceptable, then it displays Para_in.frm, else displays error message and asks for fresh inputs.
	cmd Cls	mouse_click	Clears the Picture Box area and asks for fresh drawing.
	cmdQuit	mouse_click	Terminates the operation after getting conformation from the user.
	lblArea	automatic	Displays the area of the specified cross-section, based on which machine number is chosen.
PARA_IN.FRM	comWPMat	mouse_change	The work piece material has to be selected from the drop down list provided. If the desired material does not figure in the list, user has to choose the Other.. option. The material properties then have to be specified in the INPUT BOX. If they are not within the acceptable range, MESSAGE BOX appears. Once the work piece material has been chosen, the tool material, abrasive type are shown to the user.
PARA_IN.FRM	comAbrasive	mouse_change	A proposed abrasive material is shown to the user; however the user may change it by selecting abrasive type from the drop down list. *contd...*

Form Name	Control Name	Procedures	Action Performed
	comTool Material	mouse_change	A proposed tool material is shown to the user; however the user may change it by selecting tool material from the drop down list.
	comSurface Finish Type	mouse_change	The user is required to specify the desired surface finish type by selecting option from the list. Once an option has been chosen MESSAGE BOX indicating the expected surface roughness and tolerance value is shown. If it does not conform to the user's requirement, the user can try out a different choice.
	cmdContinue	mouse_click	If all the entries in the form are acceptable, the inputs are written in a sequential file `C:\VB\inputdat' and a timer device is enabled. Otherwise, it gives error message and asks for fresh inputs for the form.
PARA_IN.FRM	Timer	activated by cmdContinue	It gives the shell command for execution of the optimization code SGA.EXE using the inputdat file. The timer device pauses the execution of the Visual Basic until the shell execution is complete. When the shell execution terminates, the output form is shown to the user.
			contd...

Form Name	Control Name	Procedures	Action Performed
OPTIMUM.FRM	lblAbrasive	automatic, once the shell exception by the previous form is completed.	Shows the final output in forms of levels. LblAbrasive shows the abrasive type to be used.
	lblGritSize	automatic	Shows the abrasive grit size to be used.
	lblConcen-tration	automatic	Indicates the optimal value of the concentration of the slurry to be used.
	lblTool Material	automatic	Displays the tool material to be used.
	lblAmplitude	automatic	Shows the optimal value of the amplitude of the tool tip
OPTIMUM FRM	lblFrequency	automatic	Shows the optimal value of the frequency of vibration of the tool.
	lblFeed Force	automatic	Indicates the optimal value of the feed force.
	lblMRR	automatic	Shows the expected material removal rate using the optimal parameters.
	lblMachining Time	automatic	Shows the expected machining time for the specified component.
	lblSurface Roughness	automatic	Shows the expected surface roughness while machining with the optimal process parameters.
	cmdSave	mouse_click	Opens the file list box in which the user has to specify the drive, directory and the name of the file in which the process plan for the given part
			contd...

orm Name	Control Name	Procedures	Action Performed
			has to be stored If a file with the same name already exists in the directory, warning message is given before overwriting it.
	cmdPrint	mouse_click	Prints the process plan in the printer using the default printer option.
	cmdEnd	mouse_click	Ends the application.

Table 4.3 : List of actions and procedures

The system flow chart indicating the inter-relationship amongst various datafiles is shown in figure 4.2.

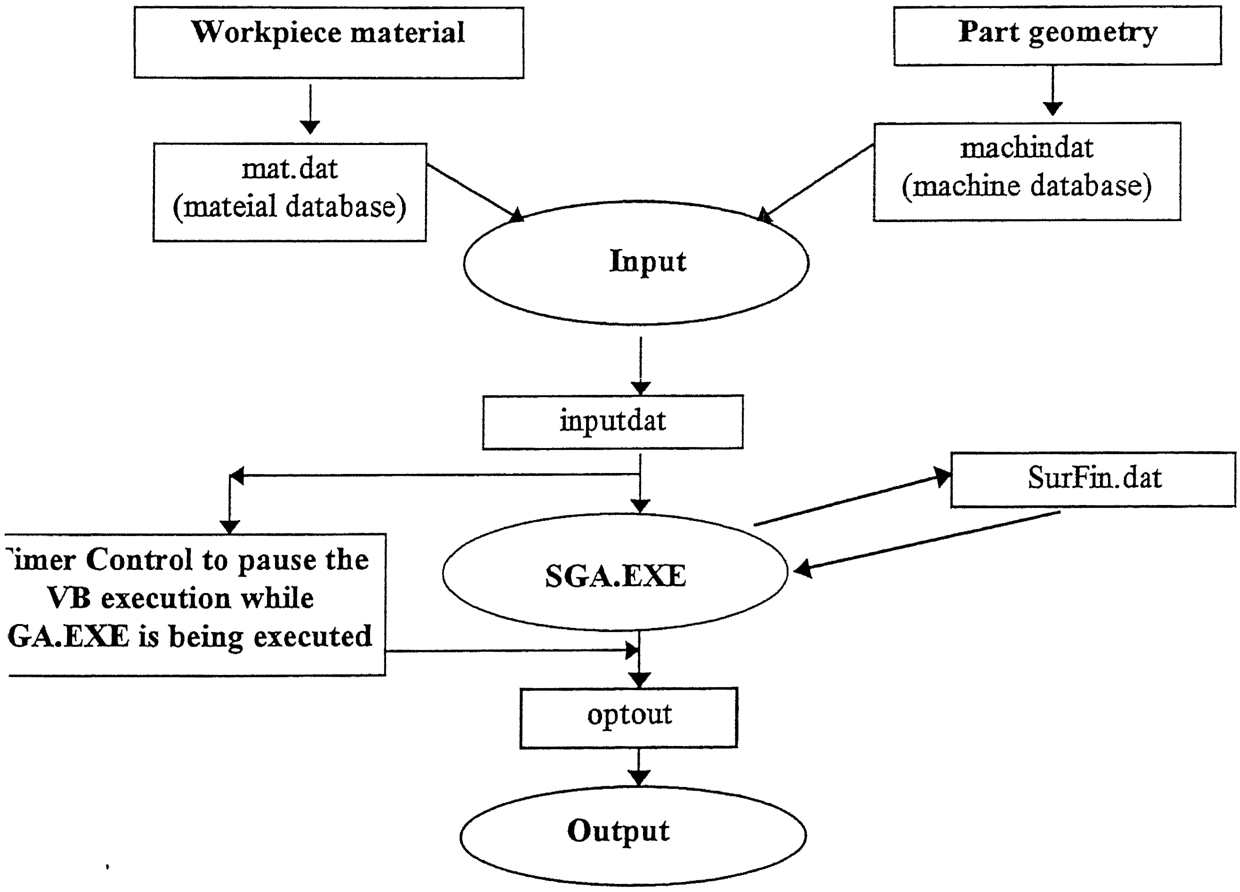


Figure 4.2 : System flow chart

4.5 Few Illustrative Examples

This section deals with a few illustrative examples to acquaint the user of the package If the execution of the system is invoked from DOS prompt, it automatically opens the Windows and show the following form.

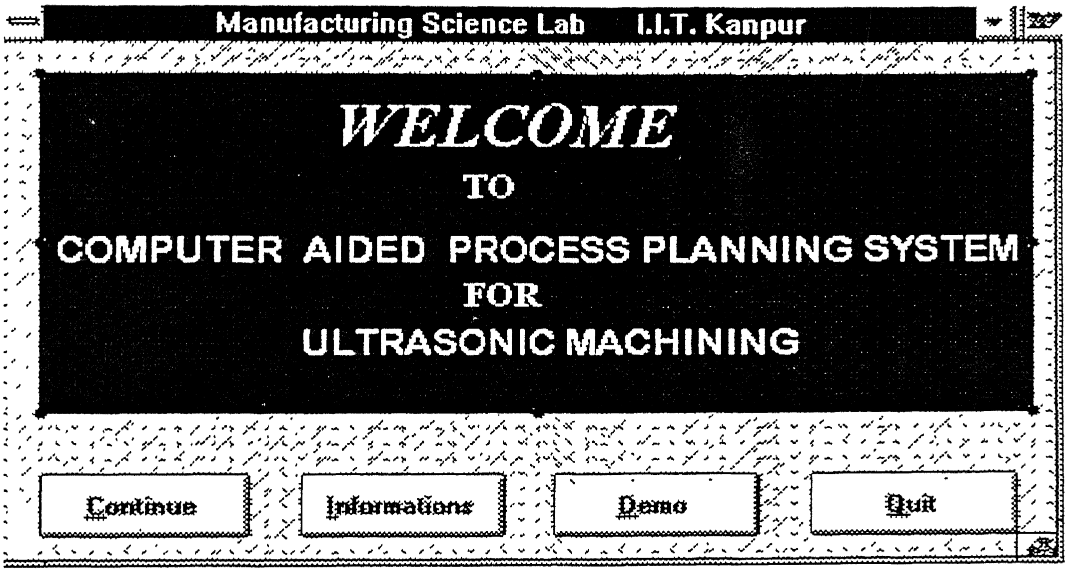


Figure 4.3 : Slide 1

The 'information' option shows the following form.

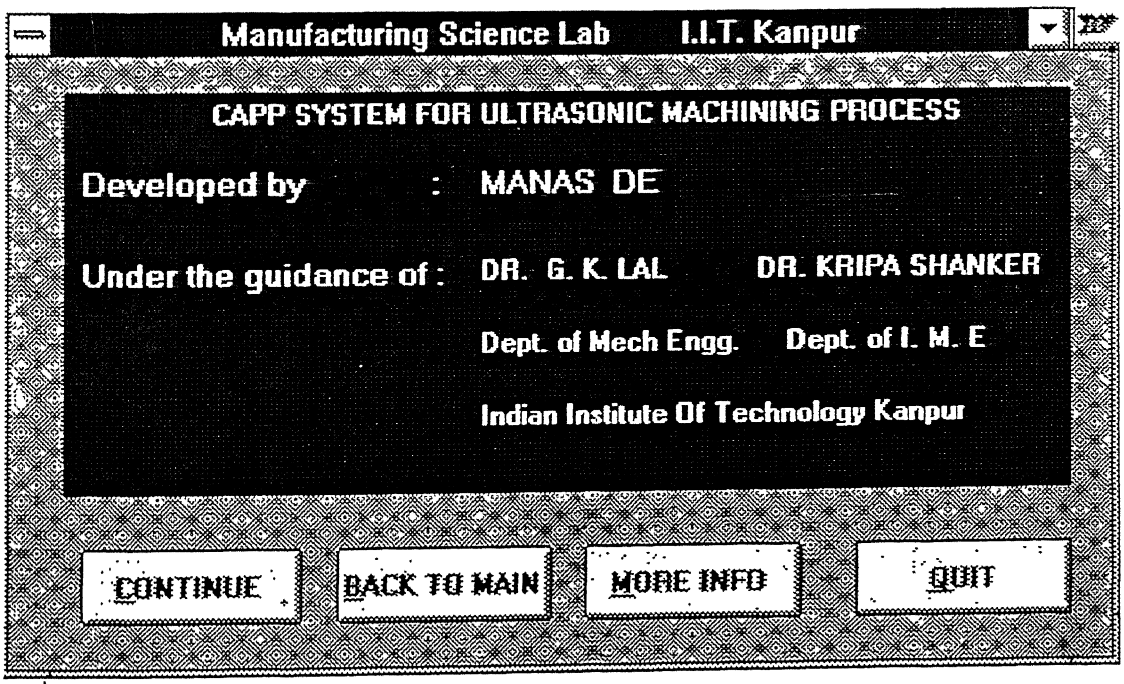


Figure 4.4 : Slide 2

To continue with the CAPP, continue option has to be selected. On selection the following form opens up on which the longitudanal cross-section has to be specified.

4.5.1 Example 1

Suppose the user specified the longitudanal cross section as shown below:

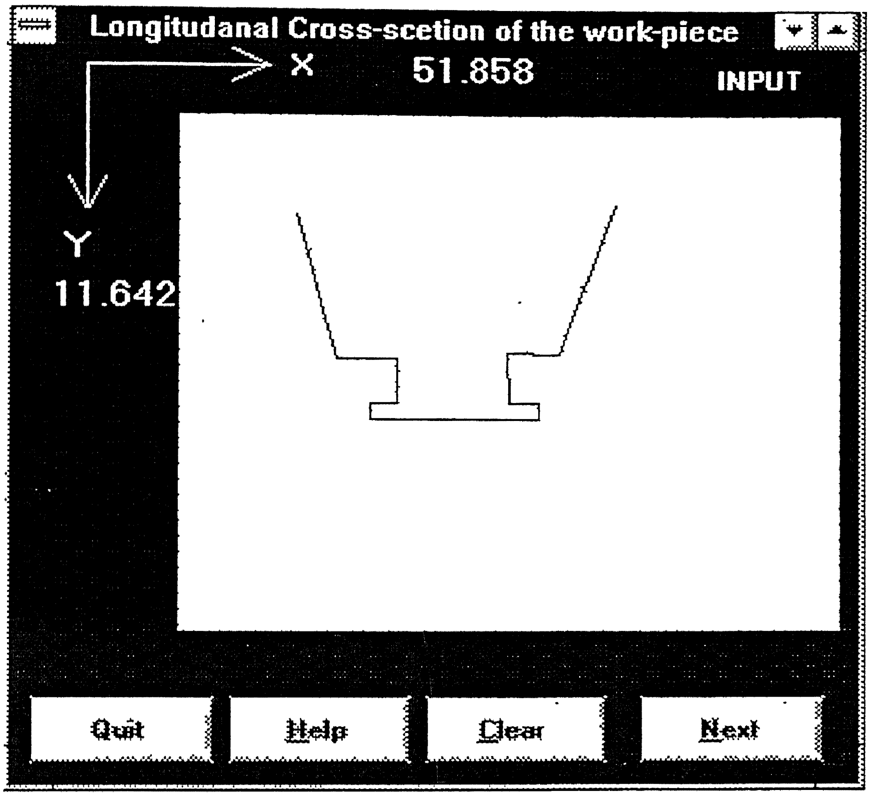


Figure 4.5 Example 1, slide 1

As it can be seen from the figure that, the collar portion is not visible from the tool approach direction. Hence, the following message appears on the screen.

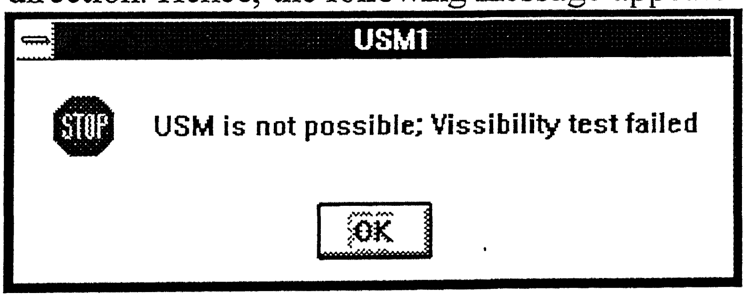


Figure 4.6 Example 1, Slide 2

So the user can either end the execution or may try out with a different part geometry by selecting the 'Yes' option from the following message box.

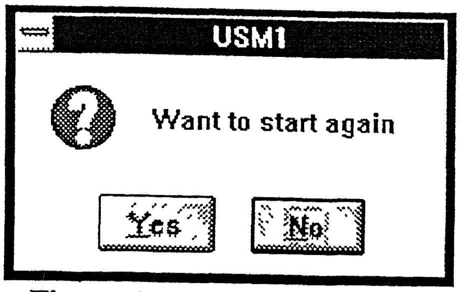


Figure 4.7 Example 1, slide 3

4.5.2 Example 2

Now let's try out with a different part geometry as shown in the following figure.

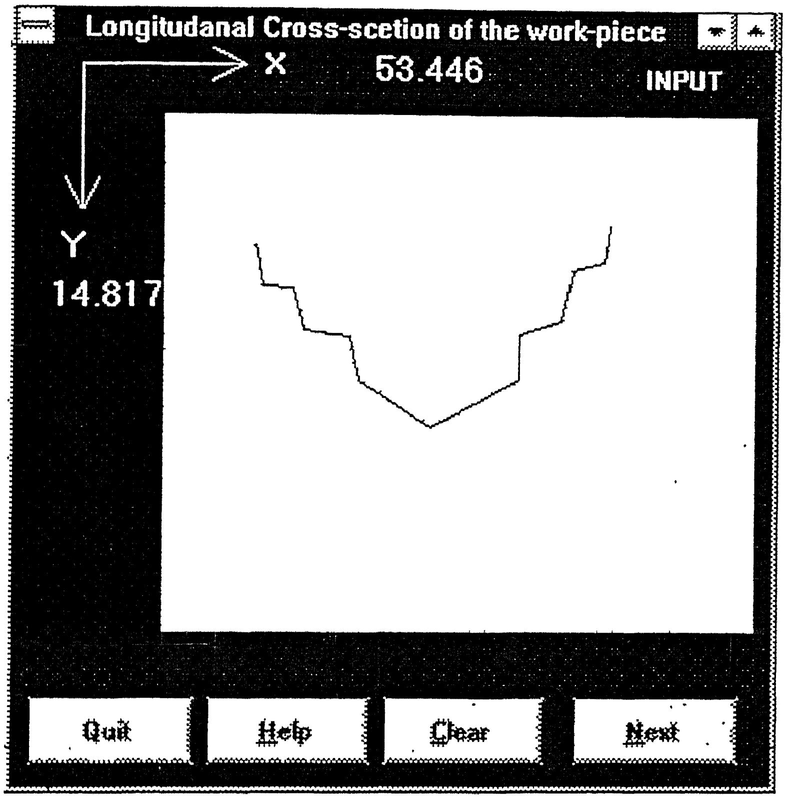


Figure 4.8 Example 2, slide 1

In this case, it crossed both Vissibility and l/d ratio tests, so the following messages appear in the screen at tandem.

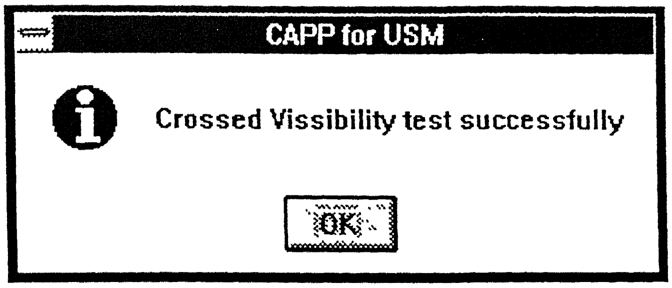


Figure 4.9 : Example 2, slide 2

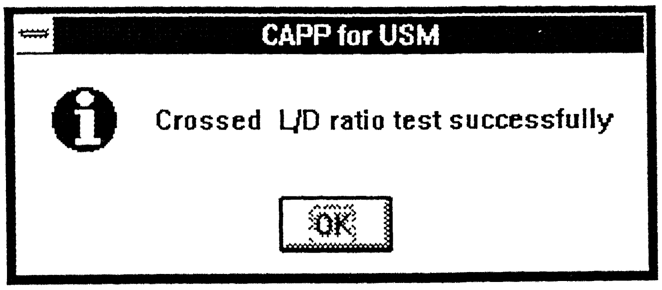


Figure 4.10 : Example 2, slide 3

Now, let the transverse cross sectional area be a regular polygon of eight sides, each side having a length of 10 mm. After specifying these inputs in the input boxes, the following slide is displayed on the monitor.

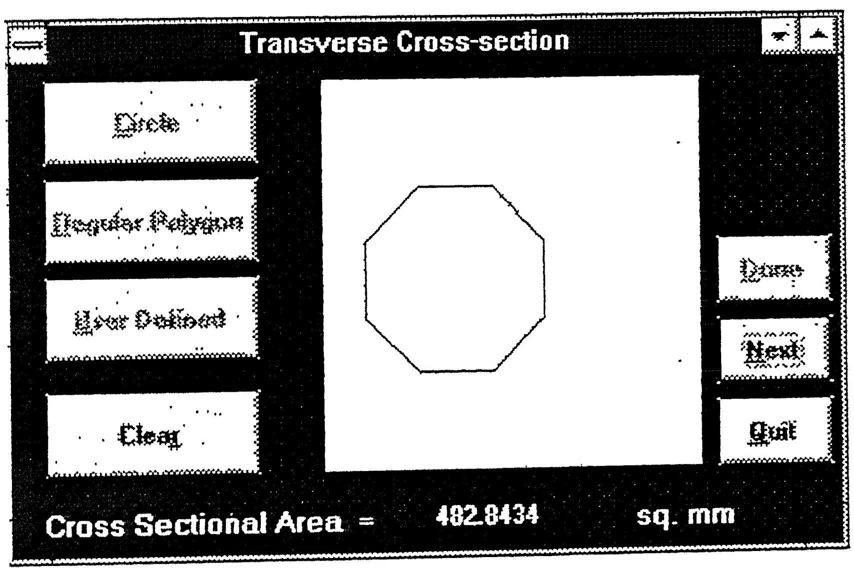


Figure 4.11 : Example 2, slide 4

After specifying the part geometry, the user has to specify a few other input parameters from the following form.

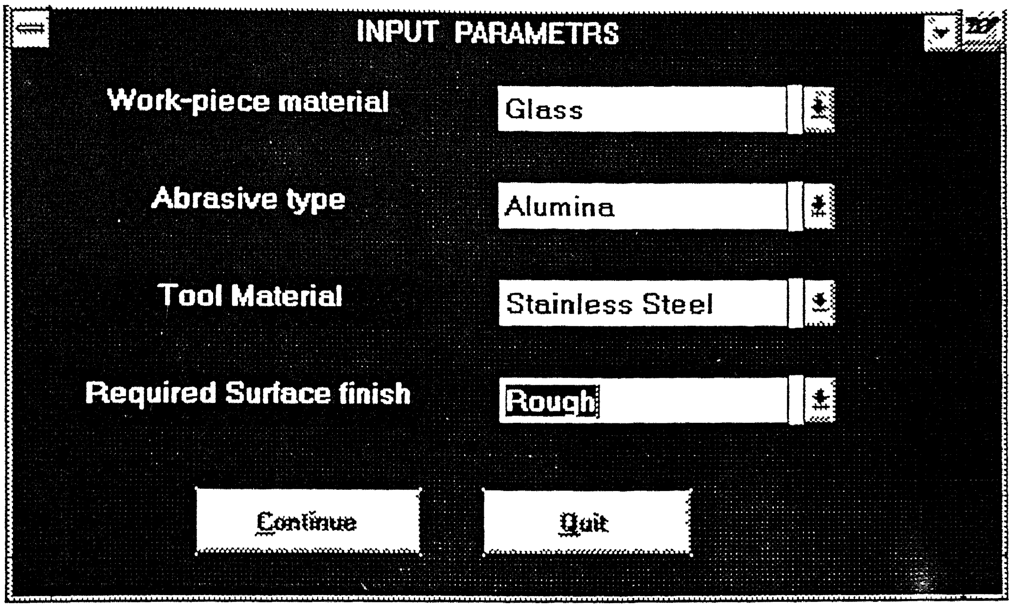


Figure 4.12 : Example 2, slide 5

After specifying the input parameters, the optimization code is executed and the final output is shown below.

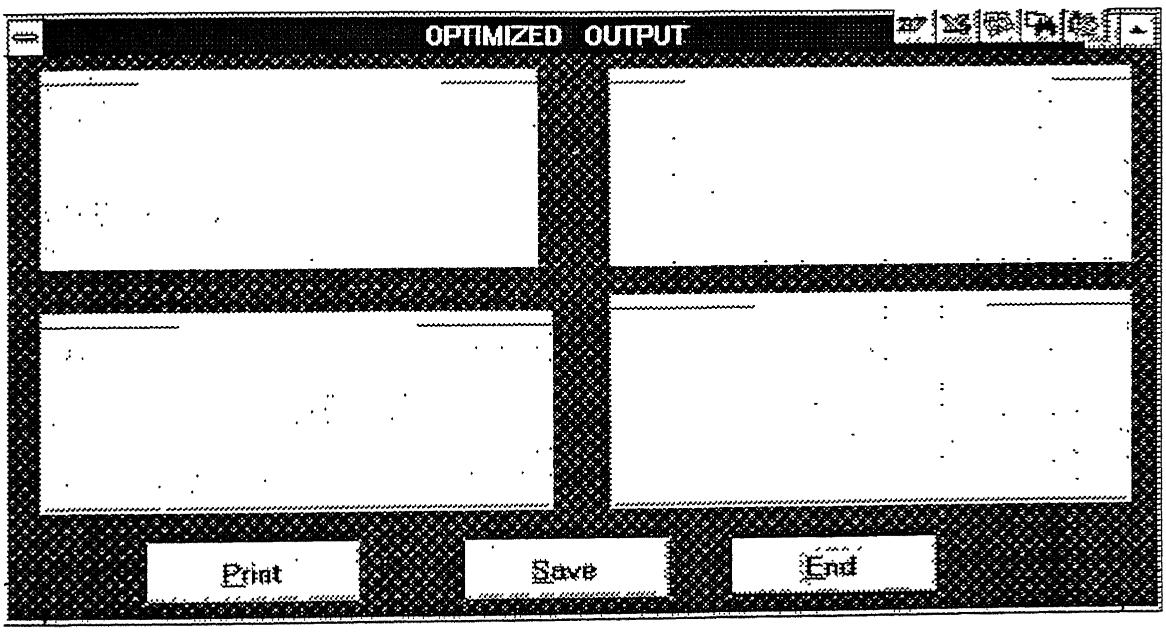


Figure 4.13 : Example 2, slide 5

After getting the final output the user can either store it in file by using the 'save' option or can take a printout by utilizing the 'print' option.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Conclusions

While developing the computer aided process planning system for ultrasonic machining, the need for a new model of material removal was felt. But since the development of an entirely new model of material removal in ultrasonic machining is beyond the scope of the present work, few modifications have been proposed.

During the entire course of development of the CAPP system, special care has been taken to make it user friendly. So that a novice in the field of ultrasonic machining is expected to end up in getting the optimal process parameter values. So with the growing popularity of ultrasonic machining in the industrial sector, this package can be of great help.

The package is an unique blend of C and Visual Basic languages. Since the computational capability of Visual Basic is limited, programs written in C language has been used to do the major chunk of computational work. Visual Basic on its part does the efficient graphic user interfacing.

5.2 Suggestions for Future Work

CAPP for ultrasonic machining is a new field. Expansion and modifications at every stage is possible. However, some suggestions are listed below.

a) The system capability id limited due to non availability of sufficient data. The system can be improved by incorporating more and more data in the material and machine database.

b) The tool wear concept can be added to the present case and the objective function can be modified to get maximum material removal rate with minimum tool wear.

c) The code can be modified to read geometric information of the part directly from Autocad or any other drawing package.

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